INDUCTIVE STORE/TRANSFORMER DRIVEN DIODE SYSTEM

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ABSTRACT

The recent demonstrations of reliable fuse/opening switch operation at high currents and short time scales suggest that inductive store/opening switch (IS/OS) circuits with their inherent advantages of small size and light weight may be appropriate for a wide variety of applications. Among these is the possibility of developing a power system for high current, high voltage diodes. While conventional IS/OS circuits can be employed, the MV voltages required make the fuse excessively long, mechanically cumbersome, and very inductive. An alternative is the use of a circuit in which the diode is driven from the secondary of a step-up transformer and the fuse interrupts the primary circuit. This paper describes the circuit analysis, design, fabrication and test of a transformer driven diode system whose objectives are 10 KA currents and 0.5 to 1.0 MV. Results of system tests in which a 60 KJ source is used to charge an 800 nH primary inductance through an electrically exploded fuse will be presented. The transformer employs a 1:6 turns ratio, and the fuse interrupts 100-200 KA currents at 200 KV to apply a voltage pulse to the load which rises in 100 ns.

INTRODUCTION

Power conditioning systems which employ inductive intermediate energy storage and current interrupting (opening) switches to gain significant increases in output power delivered to a load and corresponding decreases in current risetimes have been designed, built, tested and routinely operated at the Air Force Weapons Laboratory for use in a wide variety of applications involving low impedance plasma devices. The inherent advantages of such systems, their high energy density and relatively small components required to achieve high speeds, can be exploited for powering non-plasma loads such as electron and ion diodes and accelerator stages. As a first step in demonstrating the feasibility of such an application, this paper describes the successful design and operation of an inductive store/power conditioning system used to power a conventional high voltage electron diode. In the first section of the paper, the basic principles of the design of the system and the performance of the circuit are discussed. In the second section some results of initial operational tests are presented.

SYSTEM DESIGN AND CIRCUIT PERFORMANCE

Fast foil fuses have been employed at the AFWL as current interruptors capable of opening inductive circuits carrying megamp currents against 100's KV voltages. Average electric fields of 5-10 KV/cm are routinely supported by such fuses, while resistance risetimes of 100 nS or less (depending on circuit paramèter) are usual. Several circuit approaches can be considered to produce megavolt voltages into impedences of 25 - 100 ohms, which take advantage of the high energy density storage capabilities of inductive circuits and of the fast interrupt time characteristics of foil fuses. The simplest approach is shown in Fig 1a, where energy is stored in the inductor by current flowing in the initially closed fuse switch. Upon current interruption, power is applied directly to the cathode of a field emission diode through a series switch. This approach has the advantage of ultimate simplicity, but suffers from two disadvantages. First, the entire diode voltage must be supported across the fuse. For MV voltages, fuses several meters long are required. Such fuses, while not impossible to design and build, do make for a complicated mechanical and electrical system. Secondly, little flexibility in the choice of storage circuit values is available or since, for example, magnetic energy must be stored at the same current level as desired for the diode and the pulse width delivered to the diode is constrained to be L/Z. Since many applications involve only modest diode currents, relative large values of the storage inductor are required to store and deliver appreciable energy, and this leads to relatively long current pulses in the diode. Furthermore, primary sources suitable for charging large inductors in reasonable times are necessary, which in turn suggests charging supplies that themselves operate at high voltages. Thus the inductive power conditioning adds little in overall system performance.

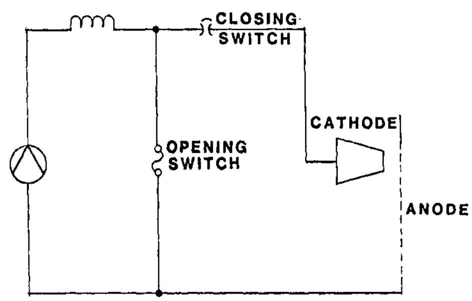

Figure 1a. Parallel Opening Switch, Direct Coupling

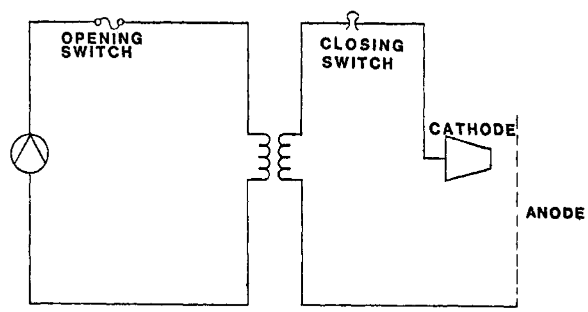

Figure 1b. Series Opening Switch, Transformer Coupling

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KA to the shorted diode. The 10% to 90% risetime of the current into the load is under 500 ns. The fuse opening switch withstands almost 350 KV, but because the diode is shorted (and low in inductance compared to the transformer secondary) the diode voltage is quite low (only 6 KV). In contrast to the shorted case, a rough approximation of power delivery to a beam load can be obtained by adding a resistance (of about 50 ohms) in series with the diode inductance to model beam impedence. Figure 5 shows the result of such a calculation. Again the peak value of the primary current is just under 300 KA, but this time the secondary current is limited to 14 KA by the "beam" impedence. The fuse opening switch must withstand only 300 KV while the secondary of the transformer delivers almost 700 KV to the anode-cathode gap of the diode.

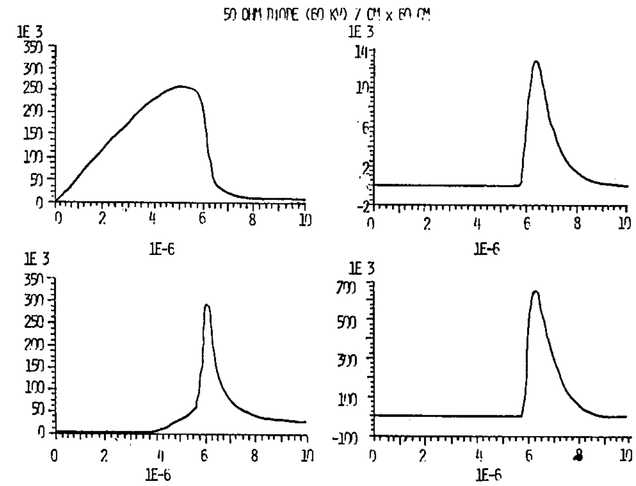

Figure 5. Diode Beam Impedance Model Performance

System Operation

Figure 6a shows a photograph of the operational system. The small capacitor bank used to drive the primary is seen on the right. The six parallel windings of the primary are seen interspersed with the continuous secondary winding in the machined double helix of the transformer core (upper center of the picture). Stacked ring diode is at the far left (coaxial with the transformer core) along with its vacuum system.

Fig 6b shows results of system tests at 35 KV charge voltage. The upper oscillogram shows the current delivered to the primary of the transformer and the lower one shows the current delivered to the diode. Current measurments are made with calibrated rogowski coils. The primary current rises to almost 120 Ka before being interrupted by the fuse at 8 microseconds after the initiation of current flow. The secondary current is zero until about the 8.2 microsecond point when the series isolating switch closes at above 100 KV and the secondary current rises to almost 6 KA. Measurements of voltage across the fuse are also made using calibrated resistive dividers. Measurement of the voltage at the cathode of the diode is made using a capacitive voltage probe located in the insulating oil jacket which surrounds the stacked ring insulator. The probe is operated directly into 50 ohm diagnostic cable as a dV/dt probe and integrated at the recording instrument to show diode voltage. Solid state PIN detectors are used to make time resolved measurements of X-Rays produced by the interaction of the beam with the anode of the diode as one method of confirmation of the production of an electron beam in the diode. Diode voltage and current data are analyzed to determine the impedence of the diode as another measure of diode performance.

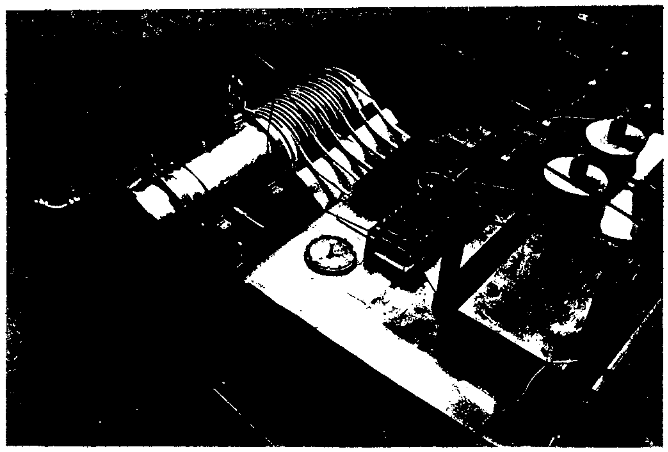

Figure 6a. Operational Experimental System

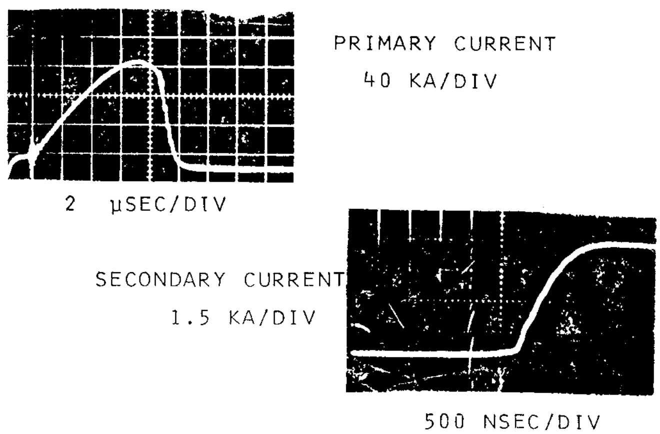

Figure 6b. Shorted Diode Test Results

Conclusion

The experiments show that a transformer driven electron beam diode can be designed built and operated as an example compact high voltage accelerator using inductive pulse conditioning technology. Operation of a megavolt - 10 KA diode system from an inductive store/opening switch power conditioning system offers important potential opportunities for design of compact accelerator and e beam sources for a variety of scientific applications. A circuit approach suitable for operation from a low inductance source such as a flux compressor device is of particular importance.

Some of these disadvantages can be avoided if the circuit in Fig 1b is employed. In this case, the primary energy source charges the primary inductance of a transformer through the fuse opening swith, and the secondary is connected to the diode through the series isolating switch. This circuit allows flexibility in the choice of charging source characteristics while still providing suitable electrical output parameters for the diode. For example, a very compact energy source in the form of a flux compression generator could be used to charge the primary inductance of the transformer. Such generators have the property of delivering very large currents to moderate inductance loads. Thus, the primary of the transformer can be low inductance, while the secondary consists of a relatively high inductance winding of many turns to achieve large voltage multiplication. This configuration has the obvious advantage of also reducing the voltage which must be supported by the fuse for a given output voltage.

An experimental system configured to test the circuit approach shown in Fig 1b was designed and tested. A small capacitor bank was used as the energy source for demonstration purposes. Major details of the system are shown in Fig 2. The transformer employed a 1:6 step-up design employing 6 parallel, 2 turn windings in the primary and a 12 turn winding for the secondary. The windings were made from commercial coaxial cable (RG218), with the outer insulating jacket and the outer woven braid removed and wound on a fiberglass core 24" long and 14" in diameter. A double-lead helix with a pitch of about 1/2 TPI was machined into the core. The secondary was wound into one lead of the helix (12 turns), while the 6 primary windings of 2 turns each were wound into the second lead, thus, making a tightly coupled air core transformer. Measurements showed a primary inductance of 820 nH and secondary inductance of about 25 microhenries, with a mutual inductance of 3.70 microhenries for a coupling coefficient of about 0.8. The capacitor bank has a total capacitance of 36.6 microfarads and stores 60 KJ of energy at a peak operating voltage of 60 KV. The bank is switched with a pair of low inductance rail gap switches and displays an internal inductance of 25 nH.

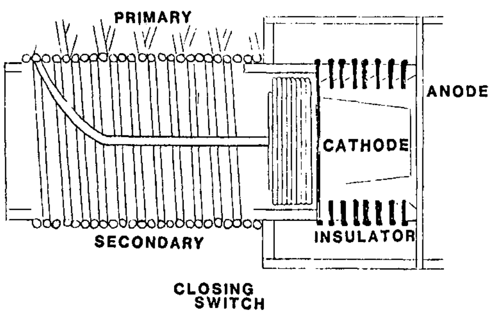

Figure 2. Transformer/Diode Configuration

The fuse opening switch consists of a foil .00254 cm (.001") thick; from 4 to 8 cm in width; and from 0.5 to 1 m long. The fuse dimensions are adjusted as a function of charge voltages such that the fuse reaches vaporization when current in the primary winding of the transformer reaches its peak value. The foil is surrounded by a layer of small, 100 micron glass beads to serve as a quench medium which cools and interrupts the fuse metal vapor upon explosion. The inductance of the fuse and its connections to the system is about 55 nH making the total inductance outside the transformer primary to be 80 nH. As a result less than 10% of the system magnetic energy is not coupled to the primary. Previous work suggests that for these dimensions the fuse resistivity should rise to 500-1000 microohm-cm making the L/R current interrupt time of the primary circuit about 100 nS.

The series closing switch is a heavy duty single channel spark gap mounted directly to the cathode. The switch is pressurized to approximately 10 psi with SF6 and closes by self-breakdown at about 150 KV.

The diode structure is coaxial with an eight element graded insulator suitable for operation to at least 1 MV. The diode inductance is 75 nH as compared with the 25 uH inductance of the transformer secondary. The cathode shank tapers to form an 8.9 diameter active cathode area at the output end. Anode-cathode gaps of 3 to 15 mm can be obtained.

A simple circuit model calculation of the performance of the system can be done by employing an elementary (empirical) model of fuse operation. Fig 3 shows the circuit model used in the calculation where a "T" equivalent circuit has been used for the transformer. An indication of the performance of the circuit in driving a low impedence load can be found by calculating the circuit solution for a shorted diode represented by a 75 - 100 nH inductance. Figure 4 shows the result of such a calculation. The peak charging current into the primary of the transformer is about 300 KA, while the system delivers almost 30

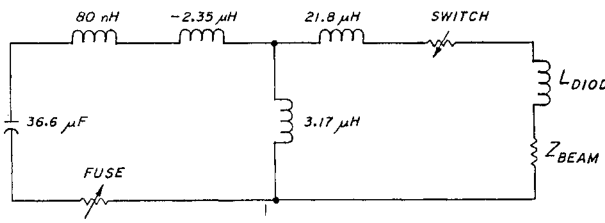

Figure 3. Transformer/Diode Circuit Model

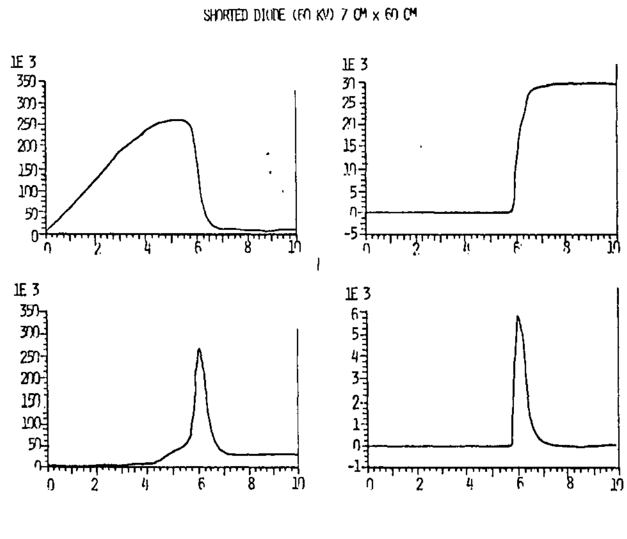

Figure 4. Shorted Diode Model Performance